Influence of the Infiltrated Rainwater on the Degradation of the Inner Wall in Hagia Sophia, Istanbul

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Influence of the infiltrated rainwater on the degradation of the inner wall in Hagia Sophia, Istanbul

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Abstract

Hagia Sophia in Istanbul has been suffering from severe degradation of the walls mainly due to salt crystallization. The objective of this research is to elucidate the degradation mechanism and propose a suitable method for preservation. From field surveys and numerical analyses of heat and moisture behaviour in the walls, it was found that high moisture—primarily due to the infiltrated rain water—generally leads to the degradation of the inner and outer walls. Moreover, it is highly possible that evaporation, mainly at the middle-layer mortar, causes salt crystallization and exfoliation of the inside stucco wall surfaces.

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Keywords: Hagia Sophia; simultaneous heat and moisture transfer; infiltration of rainwater; salt crystallization; degradation

1. Introduction

Hagia Sophia in Istanbul has been suffering from severe degradation of the inner and outer walls and the paintings on the inner wall surfaces mainly due to liquid water transport and salt crystallization. At the west side of 2nd cornice particularly, where the exterior wall was removed in 2008, there is not only exfoliation of the inside stucco and paintings but also degradation of the structure walls [1]. It is assumed that liquid and vapour water transport on and in the walls, temperature and humidity are factors contributing to the degradation. However, the

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behaviour of moisture on and within the walls and the effects of inside and outside temperature and humidity have not yet been thoroughly studied. Hence, the objective of this research is to elucidate the degradation mechanism and propose a suitable method for preservation. We report results of field surveys of Hagia Sophia and numerical analyses of heat and moisture within the walls. From these results, we consider the degradation mechanism of the inner walls.

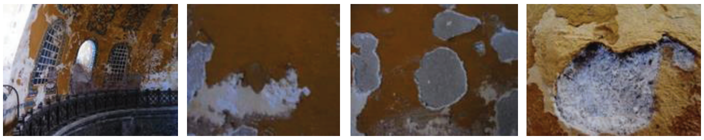


Photo 1 Degradation of the inner wall at northwest exedra

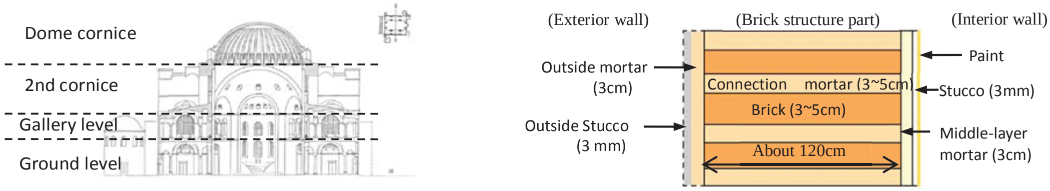


Fig. 1 Sections (left) and wall structure (right) of Hagia Sophia.

2. Field surveys at Hagia Sophia

2.1. Measurement of moisture content

The existence of water in the walls is necessary for transport and crystallization of salt. Therefore, we measured the moisture content of the inner walls at 2nd cornice where a remarkable amount of salt crystallization and degradation has been confirmed. We used a TDR moisture content meter (TRIME-FM3, S3F Surface Probe; IMKO, Germany) and measured by the sensor in contact with the stucco surface of the lower wall, where there was no painting. The location numbers are assigned at the handrail of 2nd cornice as sown Fig.2 (a). The graph in Fig. 2(b) shows the moisture content measured at the various locations in September, 2011, 2012 and 2013. Measurements at the northeastern part began in 2012. Moisture content tended to be higher at the semicircular-shaped walls called exedra, and high moisture content exceeding 20% was confirmed at the exedra in each direction. Comparing the average moisture content of each exedra, the measured moisture content was highest as the northwest exedra and lowest at the northeast exedra. There was little change in the moisture content at each of the locations over the years studied except at locations 71 and 72 at the northeast exedra.

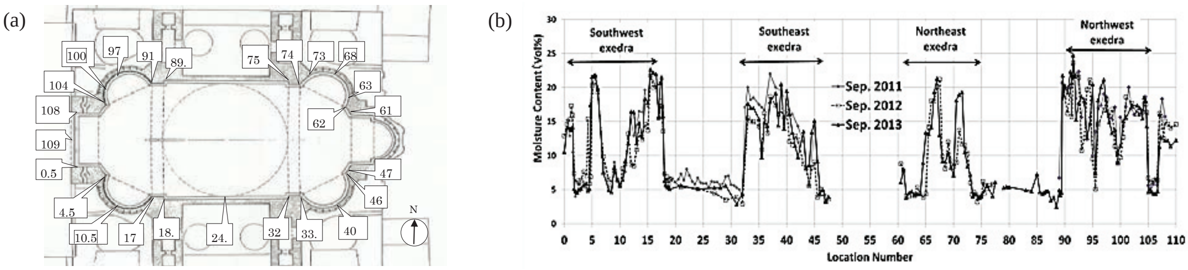


Fig. 2 Location number at 2nd cornice (a) and measured moisture content (b)

2.2. Degradation and moisture content

Ogura et al. (2012) [3] noted the relationship between the degree of degradation of the inner wall and moisture content, as locations with remarkable degradation, with exfoliation of the inside stucco or middle-layer mortar with salt crystallizations at exfoliating surfaces, generally correspond to locations of high moisture content. We examine the relationship between deterioration and moisture content including the results of a thermal image investigation. Fig. 3(a) shows a photographic image (left) and a thermal image (right) of the outer wall at location 91 of the northwest exedra a day after rainfall in 2012. Crushed connecting mortar, brick, moss and vascular plant vegetation can be seen at the lower temperature points, which are considered to evaporate on the surface and to have high moisture content. The points are considered to be corners where rainwater intensively flows down considering the shape of the roof. Fig. 3(b) shows a photographic image (left) and a thermal image (right) of the inner wall of the northwest exedra; lower temperatures were confirmed for locations 91–94, at which moisture content exceeded 20%. From this investigation, we theorized that there is a high possibility that rainwater infiltrates the outer surface and diffuses through the wall causing high moisture content and consequent degradation of the inner surface.

(a) (b)

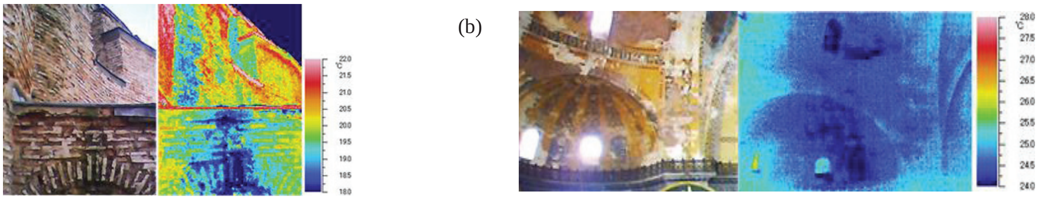


Fig. 3 Visual image (left) and thermal image (right) at the outer wall (a) and the inner wall (b) of the northwest exedra

3. Investigation from numerical analyses of simultaneous transfer of heat and moisture

3.1. Outline of analysis

Numerical analyses using simultaneous heat and moisture transfer equations for a one-dimensional model (Fig. 4) of the wall structure of the exedra at the 2nd cornice were carried out to investigate the influence of infiltration of rainwater at the outer surface. Equations (3.1) and (3.2) show heat and moisture flux [3]. A third kind of boundary condition is used for the inner and outer surfaces. Temperature, humidity and precipitation were measured every 30 minutes outside and inside Hagia Sophia from 26 September, 2010 to 25 September, 2011; these measurements were used for the boundary conditions. The moisture diffusivity and equilibrium moisture content of the connection mortar and brick were measured for samples exfoliated from the outer walls of Hagia Sophia. In this paper, the hydrothermal properties of the connection mortar were used to model the parts of the structure consisting of brick and connection mortar because connection mortar is more important for moisture transfer within the wall judging by the measured moisture diffusivities. Published values of other hydrothermal properties of connection mortar and the properties of middle-layer mortar and inside stucco were used [4, 5]. In addition, judging by the roof shape, three times the amount of the measured precipitation was assumed to flow at the outer surface of the exedra at the 2nd.cornice, and this value was used as a standard boundary condition on this analysis. Vertical surface radiation for walls facing each direction were calculated by separating the direct and diffuse components of the measured total horizontal solar radiation using Bouguer's equation (3.3) and Berlarge's equation (3.4).

Heat balance equation: $c\rho \, dT/dt = \nabla \cdot (\lambda \nabla T) + r\nabla \cdot \left(\lambda'_{\mu g}\nabla\mu + \lambda'_{Tg}\nabla T\right)$ (3.1)

Moisture balance equation: $\rho_w(\partial\psi/\partial\mu)\,\partial\mu/\partial t = \nabla \cdot \left(\lambda'_{\mu g}\nabla\mu + \lambda'_{Tg}\nabla T + \lambda'_{\mu l}\nabla\mu + \lambda'_{Tl}\nabla T\right)$ (3.2)

$c\rho$, T, λ, r, μ, ρ_w and ψ refer, respectively, to specific heat capacity for volume [J/m^3 K], temperature [K], heat conductivity [W/m K], latent heat [J/kg], water chemical potential [J/kg], water density [kg/m^3] and moisture content [m^3/m^3], and λ'_T and λ'_μ show water conductivity for temperature [kg/m s K] and water conductivity for water chemical potential [kg/m s (J/kg)]; the subscripts g and l indicate water vapour and liquid water.

Bouguer's equation: $J_{dn} = J_o \cdot P^{1/sinh}$ (3.3)

Berlarge's equation: $J_{sh} = (1/2) \cdot J_o sinh\,(1 - P^{1/sinh}/1 - 1.4 \cdot lnP)$ (3.4)

J_{dn}, J_o, P, h and J_{sh} refer, respectively, to direct radiation for a vertical surface [W/m^2], solar constant [W/m^2], coefficient of atmospheric transmission [-], solar altitude [°] and horizontal sky radiation [W/m^2].

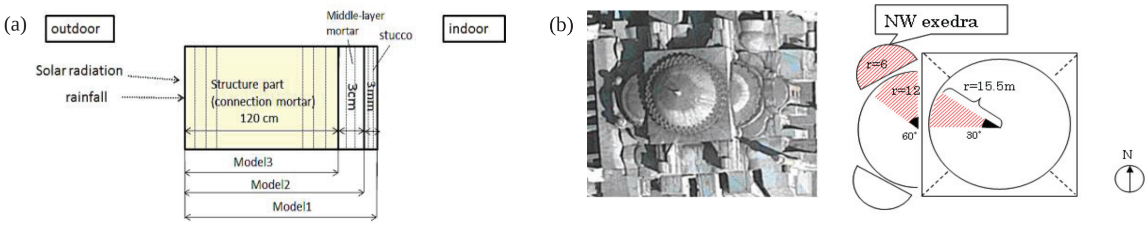


Fig. 4 Wall models for analysis (a) and the roof shape (b)

3.2. Result of calculations and discussion

3.2.1. Comparison between calculated and measured results

Fig.5 shows the calculated result of moisture content of Model 1 when 3 times the amount of measured precipitation and solar radiation of north are used as boundary conditions. The calculated point from inner surface to connection mortar (119.5cm) are approximately included in the measurement range of TDR which is about 3~5cm from the inner surface. The calculated value in the measurement range is from 0.10(m^3/m^3) to 0.25(m^3/m^3), and which generally corresponds with the measured result shown in Fig2 (b).

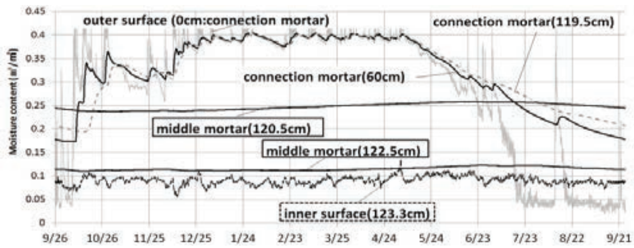


Fig.5 Annual moisture content of Model-1

3.2.2. Factors for high moisture content of the inner wall

First, we investigate factors that raise the moisture content of the inner wall considering the single-layered model consisting of connection mortar (Model 3) shown in Fig. 4(a). Fig. 6(a) shows the moisture content of the inner surface for different values of solar radiation on the north, south, west and east facing vertical walls. The moisture content of the north wall, where solar irradiation is lowest, is highest throughout the year. During winter solstice, the moisture content of the south wall is lowest, while the amount of solar radiation is highest of the 4 directions. From these results and similar ones for other directions, we can see that the amount of solar radiation, as dictated by the direction the wall is facing, affects the moisture content of the inner wall surface, as moisture content decreases when the quantity of solar radiation increases. Therefore, it is highly possible that, because solar radiation at the

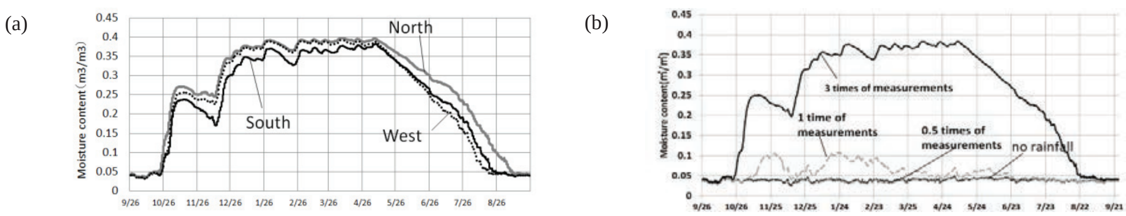
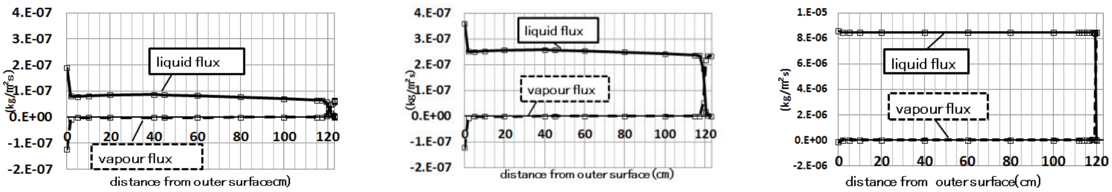


Fig. 6 Moisture content of the inner surface: (a) difference due to solar radiation; (b) difference due to precipitation

northwest exedra is lower, the moisture content of the inner wall at the northwest exedra is higher than that of the inner wall at the southwest exedra, even though the wall compositions are the same. Fig. 6(b) shows the moisture content of the inner surface when different amounts of water and solar radiation of the north wall are used as boundary conditions. There is a large difference in moisture content in the winter season because of the difference in precipitation flow on the outer wall; when precipitation is assumed to be 3 times the measured precipitation, the moisture content is more than 20% higher than that of the measurements. Thus, we believe that rainwater flowing down the outer surface greatly influences the moisture content of the inner wall.

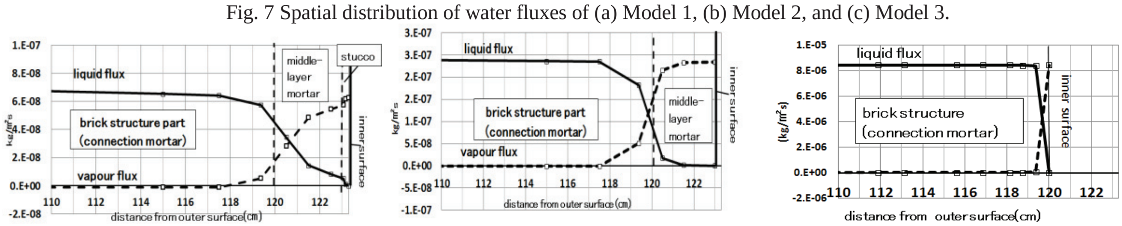
3.2.3. Investigation of crystallization location

As this study focused on salt crystallization due to evaporation of water in the walls, we discuss the location of salt crystallization based on analyses of evaporation location. Therefore, we examined the location of evaporation considering the spatial distribution of liquid water flux and water vapor flux in the wall to elucidate the degradation mechanism at the northwest exedra. We examined three different models; Model 1 is the state before degradation, Model 2 is the state in which the inside stucco is exfoliated, and Model 3 is the state in which the inside stucco and middle-layer mortar are exfoliated as shown in Fig 4(a). As boundary conditions, solar radiation of a north-facing wall and three times the amount of measured precipitation are used. In this paper, the evaporation point in the wall is defined as the point at which the following three conditions are observed at the same time and at the same location: (1) the directions of liquid water flux and vapour flux are the same, (2) liquid water flux decreases and (3) water vapour flux increases. From the analyses results, though the quantity of evaporation changes throughout the year and a maximum is observed in the summer, the evaporation point of the walls around the inner surfaces do not change. Therefore, we examined the evaporation position using the value for the annual average of the spatial distribution of water flux in the wall. Fig. 7 shows the results of water flux for each model, considering flux from the outside to the inside as positive flux. The amount of water flux increases, so the layer of exfoliation of the inside finishing materials increases (Model 1 < Model 2 < Model 3). Therefore, we assume that the amount of evaporation and consequent risk of salt crystallization increases, so the exfoliation layer increases. In addition, evaporation is assumed to occur at surrounding the inner surfaces. Fig 8 shows details for spatial distribution of water flux around the inner surfaces. The evaporation point for each Model is different: For Model 1 it is at middle-layer mortar, for Model 2 evaporation is at the boundary between the structure part (connection mortar) and middle-layer mortar, for Model 3 it is at the inner surface.



(a) Model 1 (b) Model 2 (c) Model 3

Fig. 7 Spatial distribution of water fluxes of (a) Model 1, (b) Model 2, and (c) Model 3.



(a) Model 1 (b) Model 2 (c) Model 3

Fig. 8 Spatial distribution of water fluxes around the inner surface of (a) Model 1, (b) Model 2, and (c) Model 3

In addition, we investigated the influence of changes in rainfall outside on evaporation. In this numerical analysis, Model 1 and solar radiation of the north wall were used. Fig. 9 shows the spatial distribution of moisture flux around the inner surface when different amounts of rainwater were used for the boundary condition. The calculated water fluxes were almost the same for the amounts of precipitation considered in Section 3.2.1, except for 0.1 times the measured precipitation. For 0.1 times, to some extent, the flux was less, and consequently, evaporation in the wall can be assumed to be restrained. However, there is still a possibility that the deterioration may gradually progress at the inner layer of the brick structure. Besides, there is a tendency for the evaporation location to get closer to the inner surface as precipitation increases. In addition, evaporation may get concentrated at a specific location because change inclines in the amount of vapor fluxes and liquid fluxes become larger as precipitation increases. From the above investigation, it appears that the risk of salt crystallization due to evaporation falls as the amount of rainwater at the outer surface becomes small.

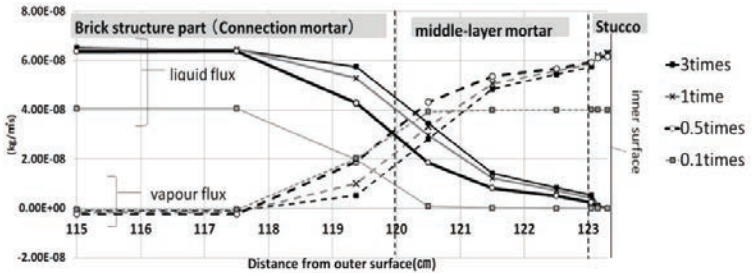


Fig. 9 Spatial distribution of water fluxes around the inner surface for different precipitation amounts.

4. Conclusion

In this paper, we presented long-term field survey results and numerical analyses of heat and moisture behaviour at the walls of Hagia Sophia to clarify the factors influencing degradation and the degradation mechanism at the inner wall at the 2nd cornice. The main results of the field survey suggest the following:

・High moisture content in the wall surface layers–primarily due to penetration of rainwater–generally corresponds to degradation of the walls and paintings. Degradation is observed at the outer and inner surfaces of walls at which rainwater flows outside and moss and vascular plant vegetation occurs.

The main results obtained from numerical analyses are given below:

・The moisture content of the north inner wall is higher than that of the south inner wall because of less solar radiation.

・There is a high possibility that evaporation at the inner wall is enhanced by increased evaporation after the inside finishing material exfoliates.

Therefore, we conclude that the amount of runoff rainwater on the outer wall enhances moisture content and evaporation around the inner surface, and degradation by salt crystallization might be prevented by controlling the amount of runoff rainwater.

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